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Tracer Puff Dispersion at Launch Sites

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13. ABSTRACT (*Maximum 200 words*)

As part of the USAF Atmospheric Dispersion Model Validation Program (MVP), puffs of tracer gas were released from a blimp over the rocket launch sites at Cape Canaveral AS and Vandenberg AFB. Multiple infrared cameras imaged the transport and diffusion of the puffs. The imagery is being analyzed to determine the position, movement, and growth of the puffs with time. The objective of the activity is to correlate atmospheric diffusion rates with measurements of atmospheric turbulence. Results of the activity will be used to evaluate and improve the models that are used at the launch ranges to predict the dispersion of toxic clouds generated by launch operations. This is the first time that tracer gases have been released from a free-flying blimp and imaged by infrared cameras at ground locations.

14. SUBJECT TERMS

Rocket Exhaust Effluent Dispersion Model (REEDM), Atmospheric dispersion Model Validation Program (MVP), Tracer, Sulphur hexafloride (SF_6), Blimp, Imagery, Puffs

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1. Introduction

This report describes a series of atmospheric tracer gas releases conducted at Cape Canaveral Air Station (CCAS) and Vandenberg Air Force Base (VAFB) to characterize local dispersion parameters. An airship (blimp) released puffs of sulfur hexafluoride while a series of ground-based infrared cameras imaged the puffs' dispersion. Analysis of the simultaneous multi-perspective imagery quantifies the absolute crosswind and alongwind dispersion of individual puffs as well as the relative dispersion of groups of puffs. These imagery-derived dispersion data provide values for the turbulence intensity. Comparison of these imagery-derived turbulent intensities to values derived by other methods (i.e., from meteorological data) and to model predictions provides the basis for tuning the atmospheric dispersion models in use at the launch sites.

1.1 Model Validation Program

Range safety offices at CCAS and VAFB use atmospheric dispersion models to predict toxic hazard corridors for space launches. The safety offices may recommend launch holds when predicted corridors extend into public areas. The Launch Programs Office at the Air Force Space and Missile Systems Center (SMC/CL) is conducting the Atmospheric Dispersion Model Validation Program (MVP) to review and improve model predictions. MVP activities are coordinated by an integrated product team, which is funded primarily by SMC/CL and the USAF Research Laboratory. Other key MVP participants include the range safety offices at CCAS and VAFB, NOAA, NASA, ACTA Inc., Kamada Science & Design, and SRS Technologies. The MVP involved two field efforts: (1) collection and analysis of launch cloud data (see References 1–15) and (2) collection and analysis of tracer release data. This report discusses the collection and quantitative analysis of the tracer release imagery.

MVP conducted four three-week tracer dispersion sessions to simulate the dispersion of toxic launch gases under a variety of meteorological conditions. Three of the sessions were conducted at CCAS (July 1995, November 1995, and April/May 1996), and one of the sessions was conducted at VAFB (May 1997). Plumes and puffs of an inert, invisible tracer gas (sulfur hexafluoride) were released in small quantities from an elevated blimp (i.e., 500 to 3300 ft or 150 to 1000 m AGL). A total of 92 plumes (each about two hours in duration) and 256 puffs were released during different times of the day and night. Aircraft and ground vehicles equipped with tracer detectors tracked the dispersing plumes and quantified plume profiles and concentrations. Infrared cameras located at multiple ground sites recorded imagery of the dispersion of the puffs. Analysis of this imagery quantifies the dispersion rates in along- and crosswind axes for each puff.

A comprehensive meteorological dataset was collected to compliment the tracer dataset. Data collected from the extensive range meteorological systems were supplemented by data from NOAA aircraft, sodars, and surface energy flux stations. All of the tracer dispersion and meteorological data collected during the four tracer sessions are being processed and posted on a NOAA web site.

1.2 Field-Deployable Quantitative Infrared Imagery Systems

The Surveillance Technologies Department of The Aerospace Corporation's Space and Environment Technology Center developed the visible and infrared imaging systems (VIRIS) to support the MVP. Each VIRIS contains a co-aligned Hitachi visible CCD camera and an AGEMA Thermovision 900 infrared scanner. The visible CCD camera enables the tracking of exhaust clouds using scattered visible solar radiation (i.e., during daylight hours). The long-wavelength infrared scanners (i.e., sensitive over the 8–12 μm band) enable the tracking of clouds and chemicals using their thermal signature (i.e., during daylight or at night). For the sulfur hexafluoride (SF_6) tracer releases discussed in this report, a narrowband filter provided improved sensitivity for the SF_6 absorption near 10.6 μm (940 cm^{-1}). The VIRIS provides not only co-aligned and simultaneous visible and infrared imagery but also collects GPS data (time and VIRIS position) along with angular data (azimuth and elevation of the VIRIS tripod). The VIRIS imagery can be interpreted quantitatively by using the encoded time, camera position, tripod azimuth, and tripod elevation to calibrate not only the field-of-view (FOV) of the cameras but also the pointing angles relative to absolute references.

The AGEMA Thermovision 900 LW scanner downloads a 12-bit digital signal to the controller. The 20° by 10° lens provides a spatial resolution of 1.5 mrad (0.09°) at 50 % modulation, while the 40° by 20° lens provides a spatial resolution of 3.0 mrad (0.17°) at 50 % modulation. Without filters, the scanner's thermal range is –25 to +2700°F (i.e., –30 to +1500°C). The scanner has a 6-position filter cassette to allow targeting narrower bands (i.e., chemical-specific detection) or hotter temperatures. The scanner supports a 15-Hz data rate with a 230 by 136 line resolution. However the image is interpreted to 272 pixels per line (i.e., square pixels). The Mercury Cadmium Telluride (MCT) detector is cooled using a Stirling cycle system.

1.3 Processing of Quantitative Infrared Imagery

The analysis of the infrared imagery involves FOV calibration, angular calibration, and analysis of simultaneous imagery. Pairwise analysis of simultaneous imagery of a puff from multiple sites provides the triangulated position and extent of the puff. The PLMTRACK program was developed by Brian P. Kasper of Aerospace for the MVP program and was used by Robert N. Abernathy to triangulate each puff's position as a function of time. Plotting the PLMTRACK-derived position data documented the puff's speed and direction. Linear regression fits to these plots provides the puff's position as a function of time. Having a formula for the puff's position as a function of time allows the analyst to process individual images from any site without complementary imagery from other sites. The analyst assesses the accuracy of the imagery-derived puff data using various analysis schemes. The AGEMA infrared cameras collected synchronized imagery from up to four sites once every 15 s during MVP tracer releases.

2. Results and Discussion

2.1 Results of Quantitative Infrared Imagery

Figure 1 is a Cartesian plot that documents not only the locations of the imagery sites (the triangles), but also the imagery-derived puff tracks (the lines) for a series of SF_6 releases on south Vandenberg AFB. All four sites are along Santa Ynez road. Site 1 (NASA) is near the NASA radar dome; Site 2 (VHF) is at the intersection of VHF road and Santa Ynez road; Site 3 (MOTU) is at the MOTU 4 geodetic marker; and Site 4 (SY Site 4) is on a dirt road off of Santa Ynez road. The airship releases originated to the northeast and northwest of Site 1. The legend identifies each puff as S#P#, where the S# refers to the series while the P# refers to the puff in each series. Therefore, S1P1 is series 1 puff 1 while S3P2 is series 3 puff 2. On 21 May 1997, the five series were separated by 10 to 15 min, and the three puffs in each series were separated by 1-min intervals. Figure 1 documents that the puffs moved to the southeast with some variation in direction (the lines are not parallel). During this same period, the imagery-derived wind speed increased from 13 to 18 ft/s (4 to 5.5 m/s) while the imagery-derived puff bearings shifted from 145 ° to 135 ° at puff altitudes of 2625 ±80 ft (800 ±25 m) MSL.

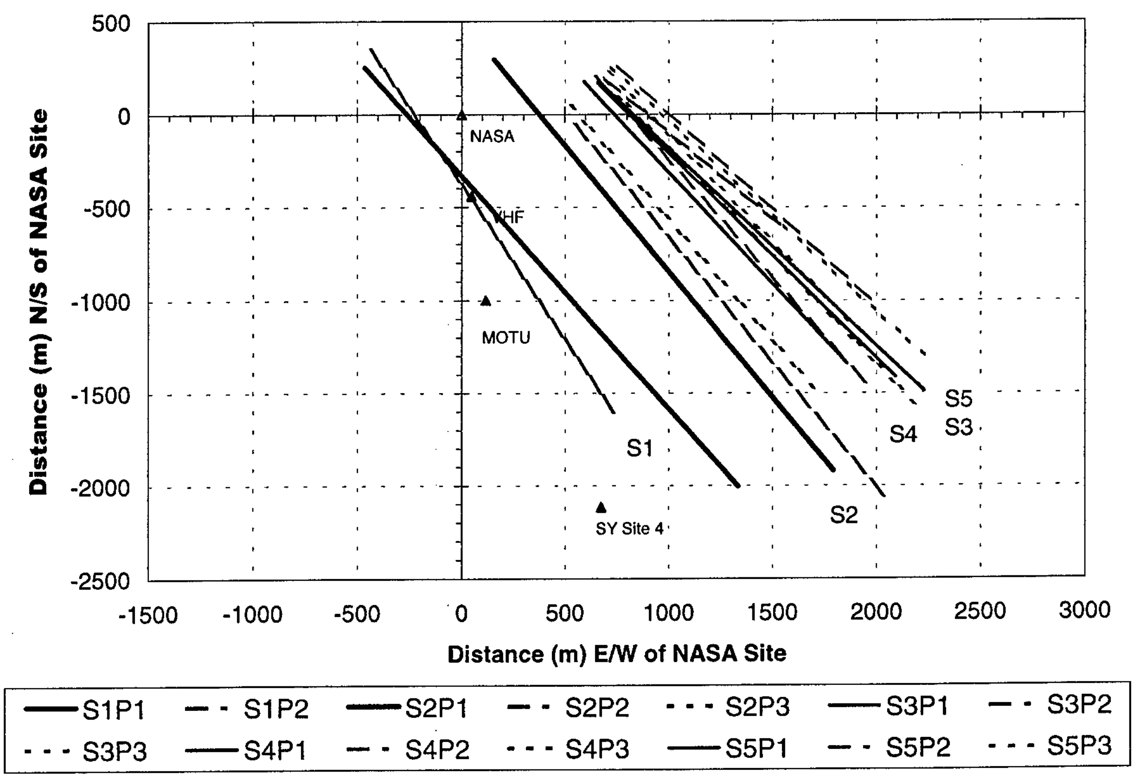

Figure 1. Puff trajectories derived from imagery of 21 MAY 1997 SF_6 releases.

Figure 2 illustrates various perspectives for viewing one series of puffs at 0.25 and 2.75 min after release of the third puff. At early times, the perspective from Site 1 (NASA site, which is closest to the release) documented the alongwind extent of the cloud as X (horizontal) pixels while Site 4 (SYSite4, which is most remote) documented the crosswind extent of the cloud as X pixels. At 0.25 min, the three puffs seem randomly oriented relative to the cross- and alongwind perspectives. Puff 1 is more than a factor of 2 larger than puffs 2 and 3 in both perspectives. By 2.75 min after the release, Site 1 viewed the crosswind extent as X pixels (and the vertical extent as Y pixels) while Site 3 (MOTU) viewed the alongwind extent as X pixels (and the crosswind extent as Y pixels). It is apparent that there is only about a factor of 2 difference in the crosswind size for all three puffs by 2.75 min. In contrast, the alongwind size is almost identical for all three puffs by 2.75 min. Quantitative analysis of the puff imagery reveals that the crosswind expansion rate is larger than the alongwind expansion rate for all three of these puffs.

Figure 3 plots the imagery-derived expansion rates (m/min) as a time series (release time for each puff) for the 21 May 1997 SF_6 puff releases. These data document a dramatic change in the relative cross- and alongwind expansion rates, followed by a slowly varying ratio. For the first puff of the first series (the earliest data points in Figure 3), the alongwind expansion rate was significantly larger than the crosswind expansion rate. As illustrated by the data in Figure 3, this trend reversed for the next puff and for all subsequent puffs on 21 May 1997. For times after 21:15 GMT, the crosswind expansion rate was 3 to 4 times greater than the alongwind expansion rate. These data document the dispersion rates for non-spherical puffs that started out with dimensions of 160 to 330 ft (50 to

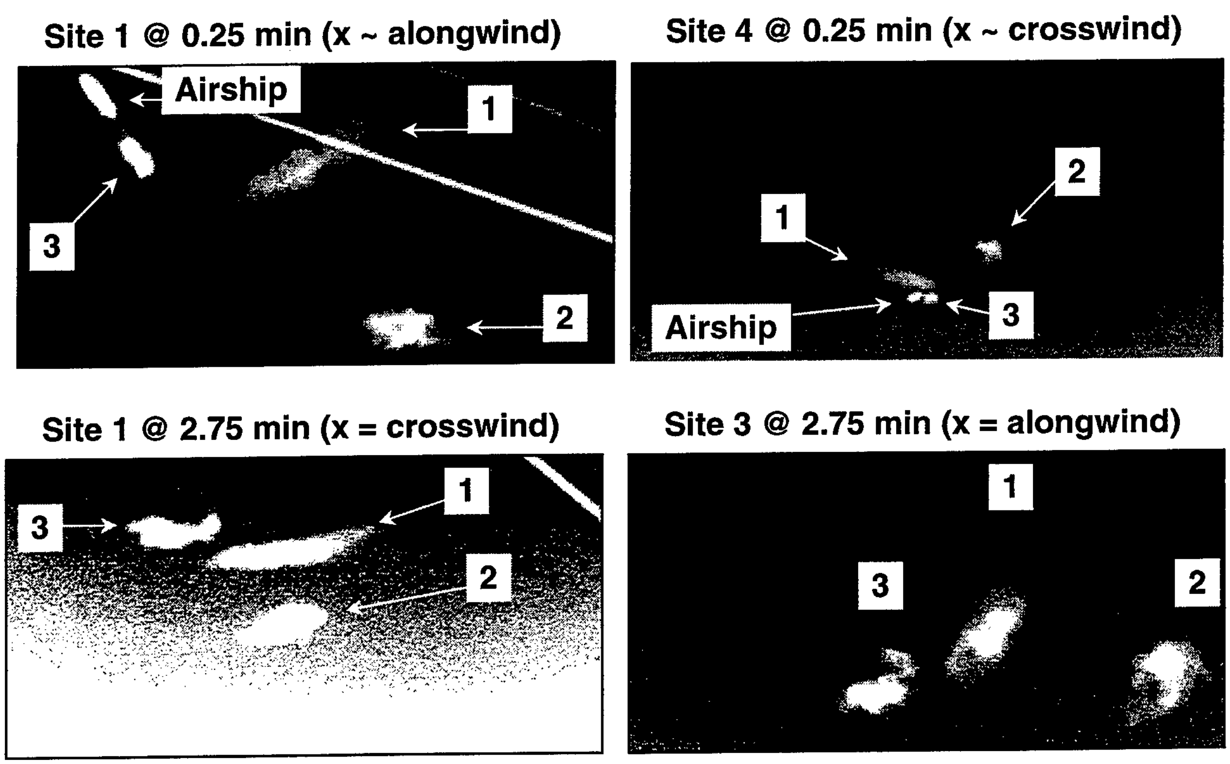

Figure 2. Imagery of puffs documenting cross- and alongwind perspectives.

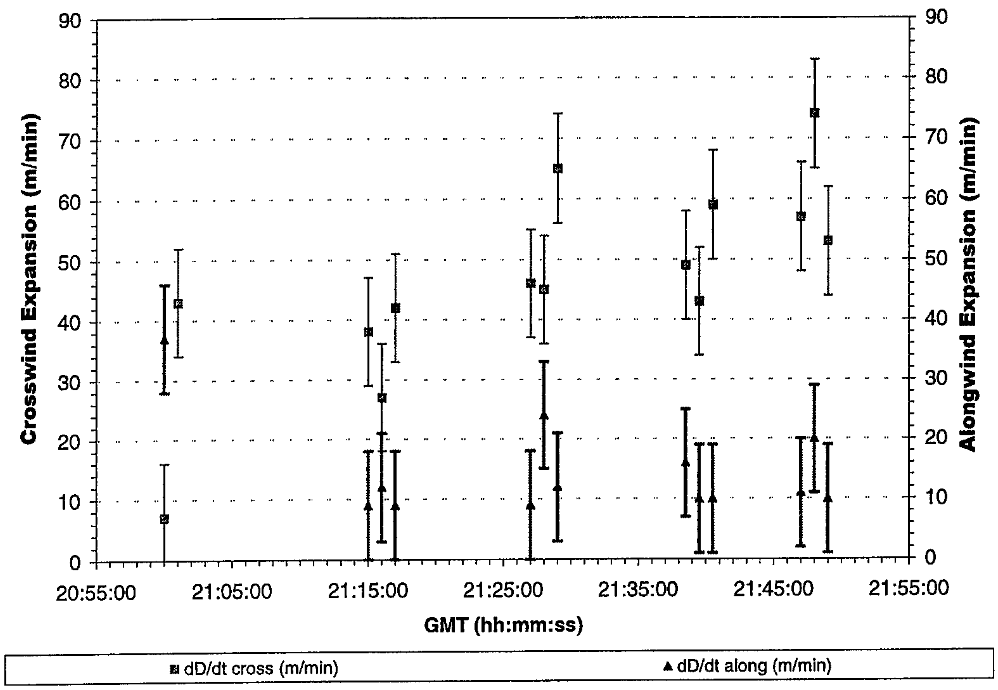

Figure 3. Puff expansion rates derived from imagery of 21 MAY 1997 SF_6 releases.

100 m) and grew to 980 to 1970 ft (300 to 600 m) over the 5 to 10 min of tracking. As illustrated by Figure 2, the puffs were released with various aspect ratios and orientations relative to the wind direction. The imagery data suggest that the expansion rates were independent of the initial aspect ratio and geometry. The data plotted in Figure 3 suggest a slowly increasing ratio of crosswind to alongwind expansion rates for times after 21:15 GMT. During this same period, the imagery documents a slow shift in cloud bearing and an increase in cloud speed.

Figure 4 documents the dispersion affecting a slightly larger scale by tracking the relative distance between puffs within each series of releases. In Figure 4, the distance between puffs is plotted against time and the rate of change (in meters per minute) is written next to each dataset. The distances between puffs ranged from 660 to 2300 ft (200 to 700 m). The data in Figure 4 document that the relative motion between puffs was less than 33 ft/min (10 m/min) for the 21 May 1997 data. The individual puff data in Figure 3 documented that the alongwind dispersion rate was less than 66 ft/min (20 m/min) while the crosswind dispersion ranged from 80 to 250 ft/min (25 to 75 m/min) after 21:15 GMT.

The data in Figure 5 document the angular information for the pairs of puffs relative to the imagery-derived crosswind (225 ° to 235 °) and alongwind (135 ° to 145 °) bearings. The data in Figure 5 document that the puffs were separated mainly in the alongwind direction. This is qualitatively consistent with the 1- to 2-min difference in their release times (each puff moved downwind until the next puff was released). Review of the data presented in Figures 4 and 5 reveals that the relative dispersion between puffs appears to be random (±33 ft/min or ±10 m/min). These data also document that the relative puff dispersion rates were low in magnitude (less than 66 ft/min or 20 m/min), similar to the alongwind dispersion rates measured for the individual puffs.

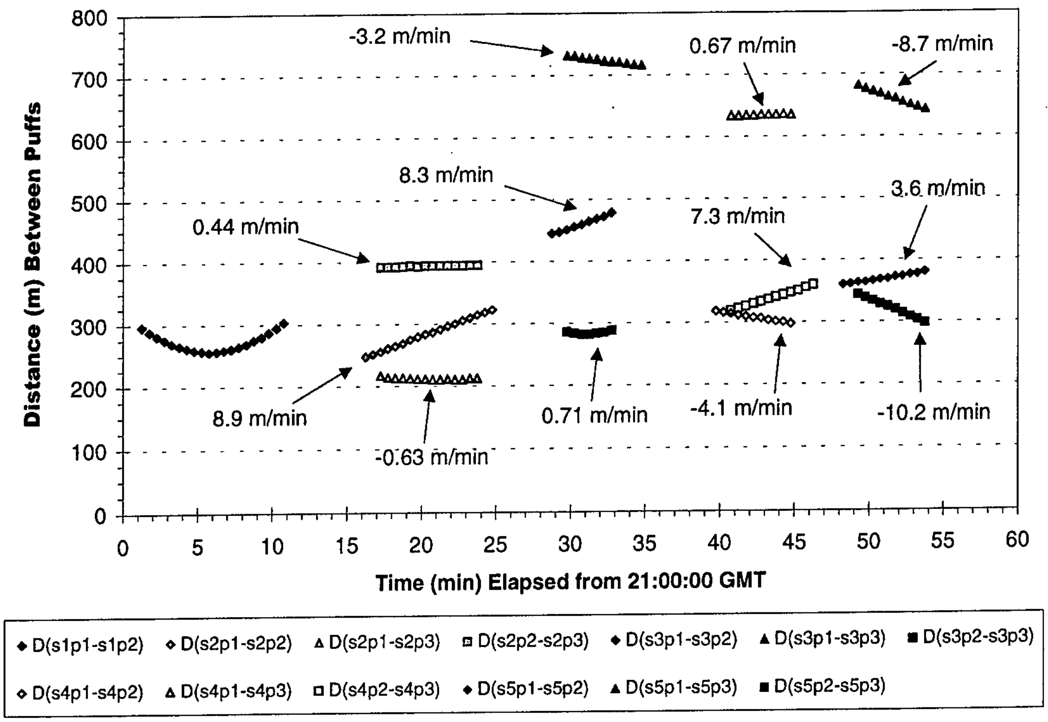

Figure 4. Relative puff spacing derived from imagery of 21 MAY 1997 SF_6 releases.

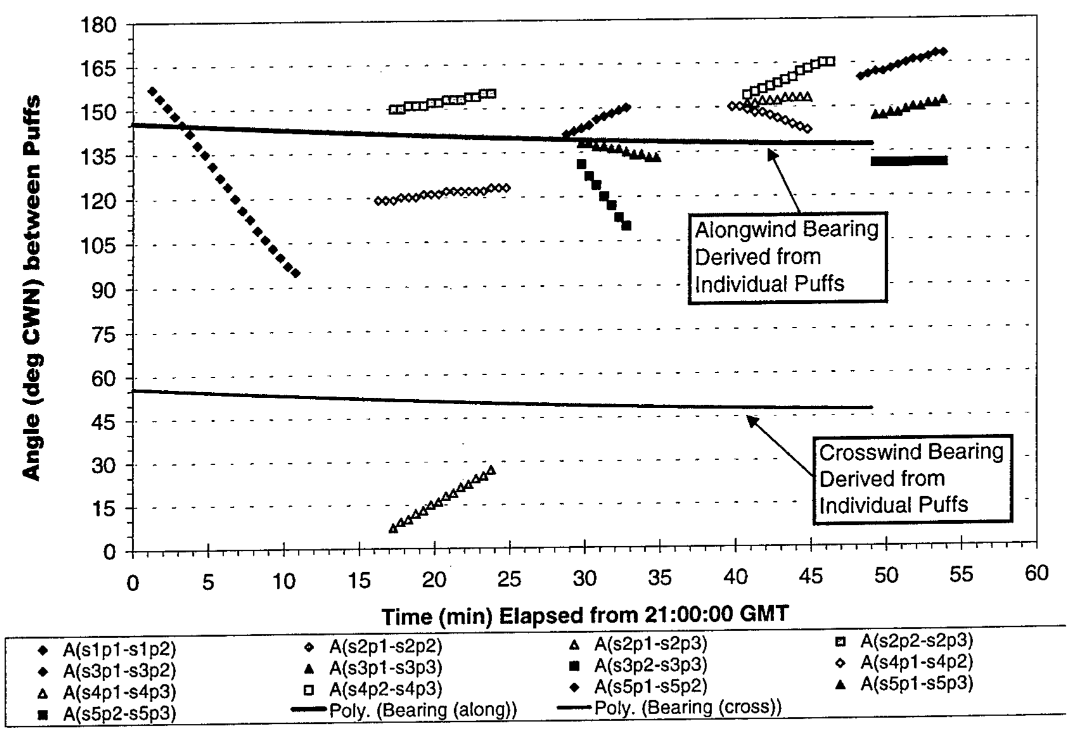

Figure 5. Angles between puffs derived from imagery of 21 MAY 1997 SF_6 releases.

2.2 Extraction of Atmospheric Turbulence Information From Puff Imagery

An estimate of atmospheric turbulence at the altitude of cloud dispersion is a key input to atmospheric dispersion models. Estimates of atmospheric turbulence fluctuations at the altitudes of interest for rocket exhaust clouds (200–700 m AGL) can be extracted directly from the puff imagery data. These values can then be compared to turbulence fluctuation values produced from other meteorological data sources. MVP collected meteorological data from numerous sources during the tracer release sessions, including meteorological towers, rawinsonde soundings, flux towers, radar profilers, sodar profilers, and instrumented aircraft (NOAA Long-EZ). Figure 6 shows how turbulence fluctuations are calculated from these data sources.

In addition, the tracer puff data can be used to evaluate and verify the performance of the REEDM built-in climatological algorithm. REEDM uses σ_u and σ_w values to calculate cloud spread rate and, hence, concentration levels. The REEDM algorithm for calculating σ_u and σ_w is a function of z (altitude). At the surface (z ~ 33 ft or 10 m), the sigmas are based either upon instrumented tower measurements or upon a climatological algorithm. In either case, adjustments are made for surface roughness. For higher altitudes, the sigmas are based upon the stability class and the height. The spread rate is based upon the RMS of the sigmas and the layer wind shear.

The processing and analysis of the tracer puff data will continue in order to reveal the strengths and weaknesses of the various methods used for calculating the turbulence intensity at the altitudes of interest. This work will lead to the development of improved methods for predicting turbulence profiles for use in REEDM and other atmospheric dispersion models used at the space launch ranges.

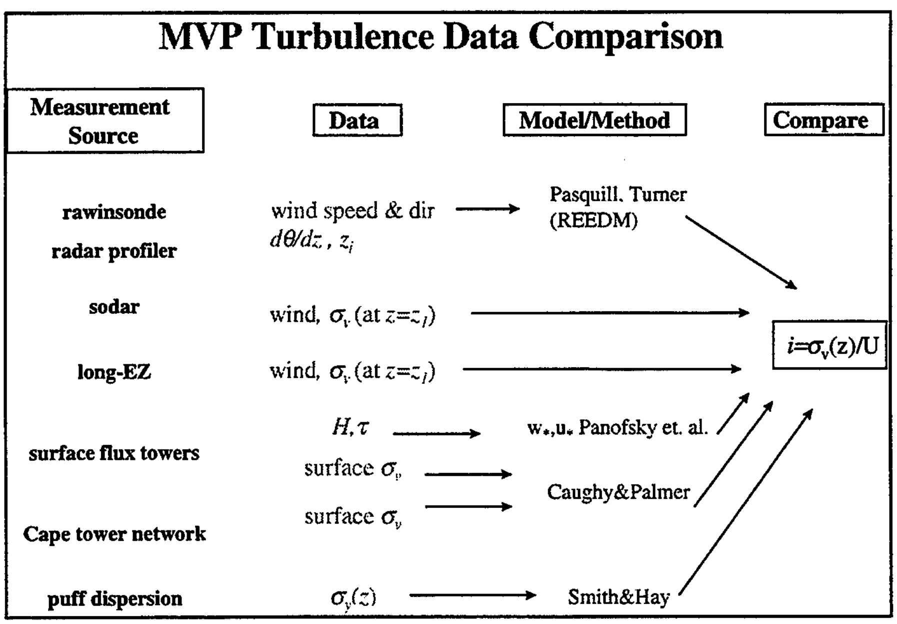

Figure 6. Flow chart for conversion of data to turbulence fluctuations.

3. Summary and Conclusions

Infrared imagery has been used to quantify the dispersion rates of tracer puffs both in the along- and crosswind axes. Atmospheric turbulence information can be extracted directly from the puff imagery data. The imagery-derived turbulence intensities can be compared with other measured and projected turbulence data. This basis of comparison can be used to evaluate and improve upon the current algorithm used for turbulent dispersion in REEDM and other atmospheric dispersion models.

We will continue to process the remaining puff data that was acquired during four tracer release sessions. The data presented in this report are a small sampling of the data collected during the four sessions. These puff data should provide an interesting dataset for challenging current and future dispersion models.

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